Observation of NLIW in the South China Sea using PIES

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LONG-TERM GOALS

To study the mechanisms of generation, evolution and propagation of nonlinear internal waves [NLIW] in the vicinity and west of Luzon Strait in the South China Sea, making use of pressure equipped inverted echo sounders.

OBJECTIVES

Our objectives are (1) to observe the internal tide propagating west of Luzon Strait and its progressive evolution in shape and speed as it traverses the South China Sea under the influence of nonlinearity, non-hydrostatic effects, rotation, topography, currents and stratification, and (2) to interpret the results in with the help of models that incorporate these effects.

APPROACH

Our approach involved deployment of four modified pressure equipped inverted echo-sounders [PIES], set up to transmit every 6s. The PIES measures the return acoustic travel time from sea-floor to surface, which is modified by variations in the local stratification resulting from passage of internal waves. Knowledge of the background stratification is provided by CTD casts. Time series measurements of the acoustic travel time then provide a basis for inferring the first mode internal response. Nonlinear non-hydrostatic models can be used to interpret the evolution of the waves as they pass successive measurement sites. Additional modeling is used to explain the generation of the internal tide measured close to the Luzon sill.

WORK COMPLETED

Four PIES were deployed in April 2007 in the South China Sea in a line stretching west northwest from the narrow trench just west of the Luzon sill the 600m contour, as shown by red dots in Figure 1. Two blue dots show the locations of two PIES deployed during a pilot study in 2005. The 2007 deployments were recovered in July and the three easternmost moorings redeployed for recovery in October 2007.

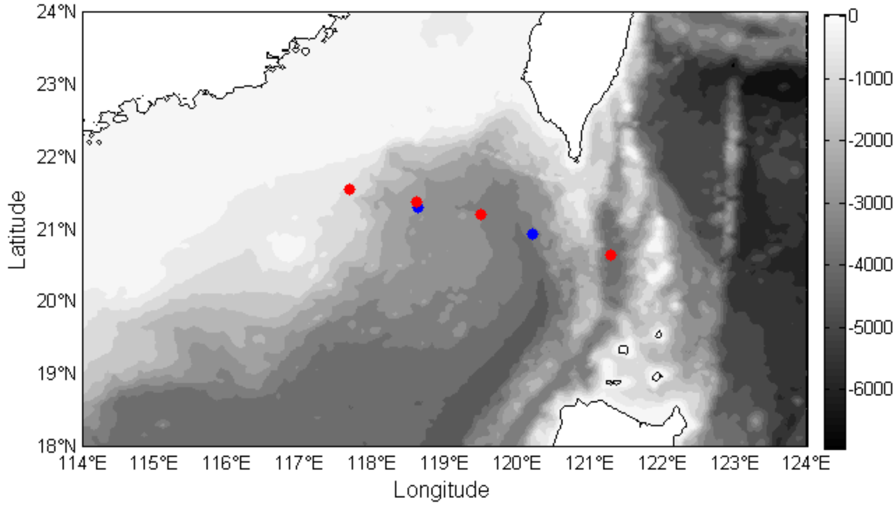

Figure 1. Chart showing locations of PIES deployed in South China Sea in 2005 (blue) and 2007 (red).

The westernmost PIES was thought to have been tilted on deployment or otherwise adversely affected, possibly due to partial burying by wave-sediment interaction on the sloping terrain. The explanation for this behaviour has only recently become apparent see below). It did not immediately rise to the surface when released in July, but was recovered a few days later some distance to the northeast and returned unharmed. The data from this instrument was not complete.

Key individuals involved in this project also include Erran Sousa (URI), responsible for technical aspects of deployments and recovery, Jae-Hun Park (URI) for assistance in implementing models, student Li Qiang (URI), and Karl Helfrich (WHOI) who has provided important theoretical support.

WORK COMPLETED

Time series measurements of baroclinic variability associated with the internal tide and its evolution were acquired with PIES deployed in the South China Sea. Model and data analysis have been completed in order to describe the performance of PIES in the measurement of nonlinear internal waves. In addition the time series observations have provided the basis for explaining the nonlinear internal tidal evolution west of Luzon Strait. The results have been presented in conferences and two papers have been submitted for publication. Preliminary work has been carried out on a further model analysis using a fully nonlinear internal wave model. In addition a further brief deployment of PIES occurred during a cruise in the South China Sea during September 2008.

RESULTS

1. Model analysis of the inverted echo sounder approach to measuring NLIW:

In order gain confidence in our interpretation of observations using PIES and to better understand their performance in the presence of interference from the rough sea surface and ambient noise, a detailed model of the instrument and its operational environment was developed. The model included key electronic components, representing the analog processing of data prior to recording. In addition we modeled acoustic propagation within the water column and scattering by the rough sea surface, and also included ambient noise associated with wind.

It became apparent, at least for the South China Sea, that acoustic propagation is virtually insensitive to all but first internal mode variability, as shown in Figure 2:

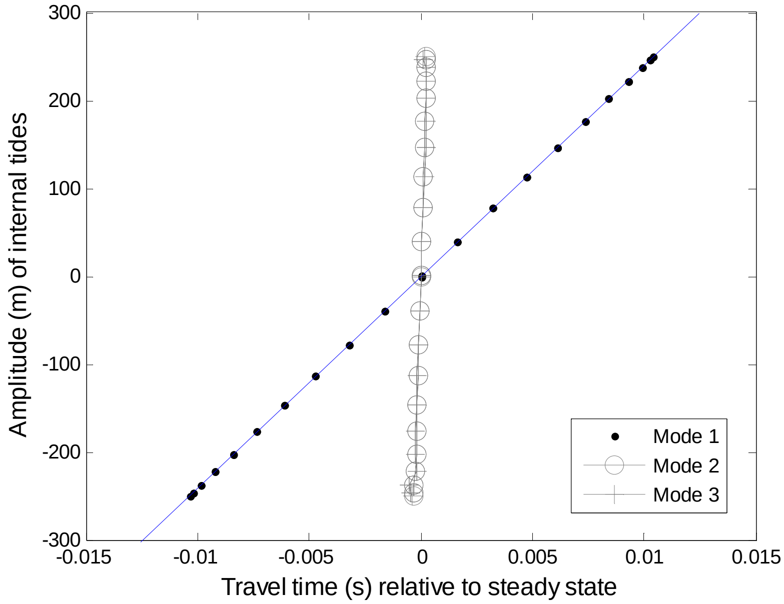

Fig. 2. Relationship between acoustic travel time and internal wave amplitude according to normal mode analysis, for observed stratification in the South China Sea and a nominal water depth of 2500m.

The instrument signal processing electronics (hard limiting, threshold detection and filtering) was modeled and the model tested in the laboratory with satisfactory results (Figure 3):

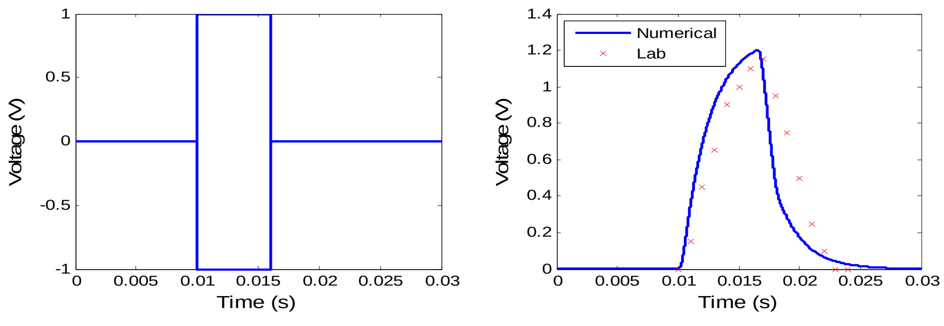

Fig. 3. Lab comparison with simulation of signal detection.

A Pierson-Moscowitz wave equilibrium wave spectrum was assumed as a nominal model for the wind dependent ocean surface, and rough surface scattering theory used to compute the shape of the scattered signal. The resulting signal was then fed to the model of the instrument electronics. Based on both observations and theoretical considerations, a Rayleigh distribution was an appropriate functional approximation to the wind speed dependence of the acoustic travel time (see Figure 4), where the wind speed is evaluated from QuickSCAT scatterometer observations. The figure includes data from instruments deployed at 3 different sites. These results incorporate expected ambient noise based on the well established Knudsen curves.

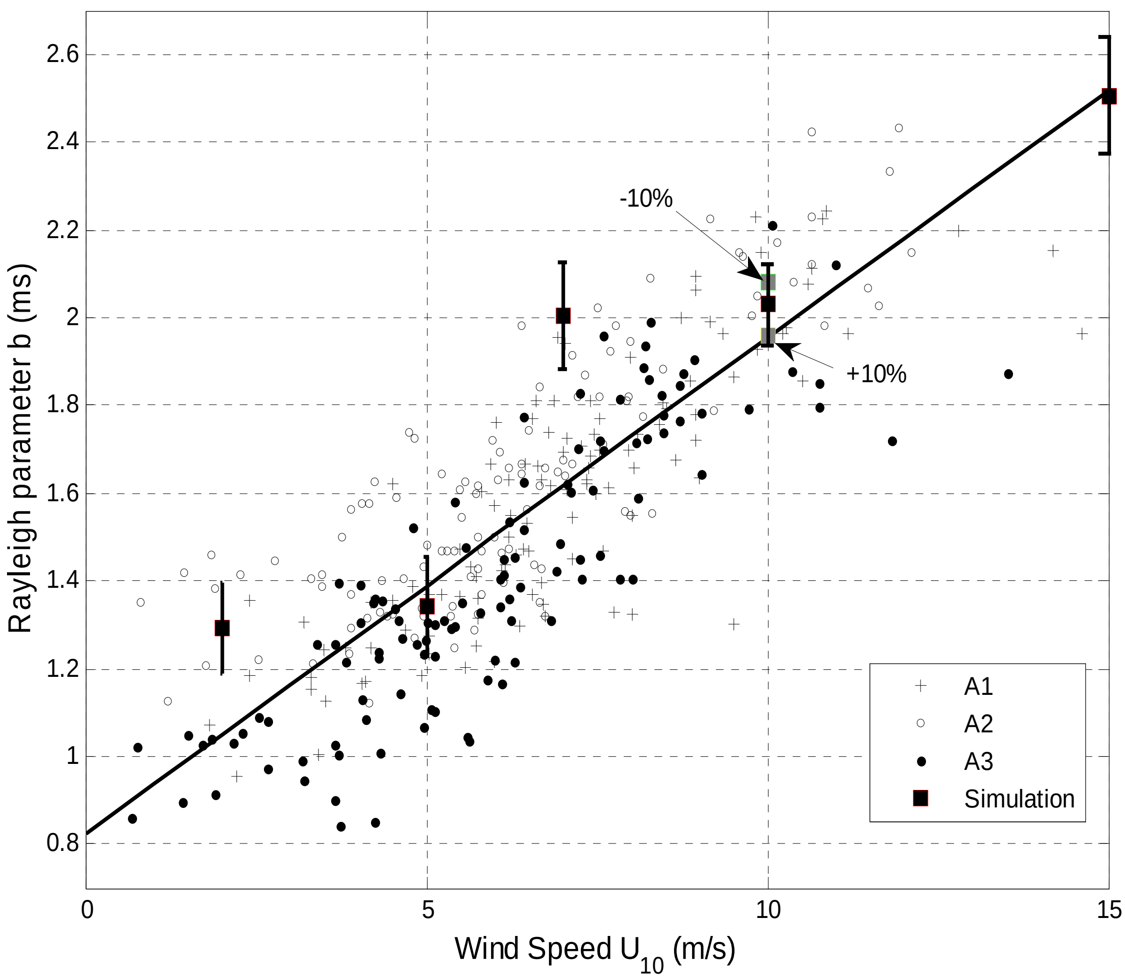

Fig. 4. The Rayleigh distribution is used to fit the observed and modeled travel times. The wind speed is acquired from the QuikSCAT and wind generated ambient noise based on the Knudesen prediction.

Having developed a predictive model of instrument performance, the results were used to evaluate instrument bias which could then be removed from the data.

2. Internal wave analysis:

Figure 5 shows a short segment of data. The expanded time series illustrates a feature of the observations west of Luzon. During this phase of the fortnightly cycle the signal

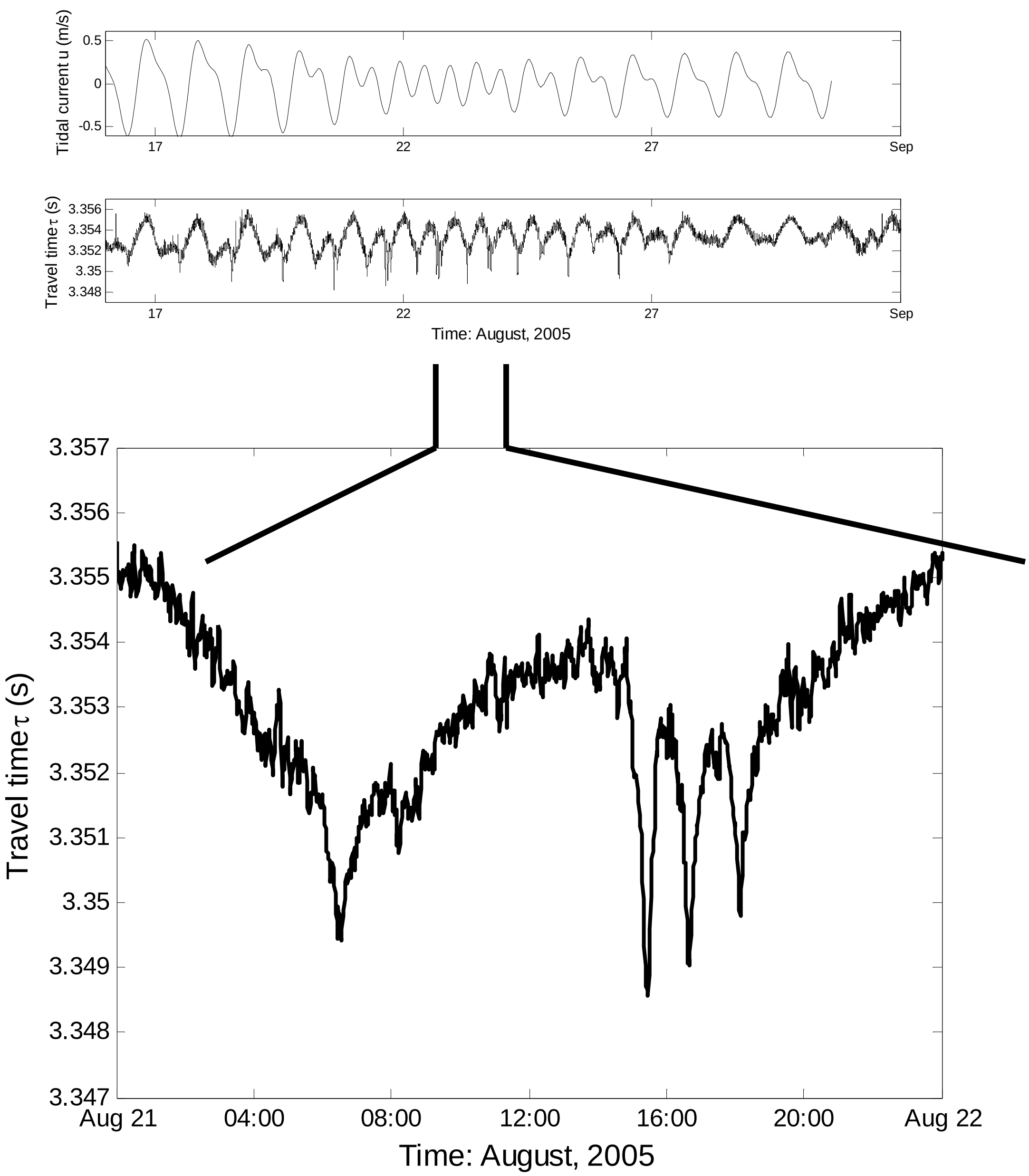

Fig. 5. Top: Zonal tidal current at Luzon Strait (122°E, 21°N) with 33 hour shift equivalent to expected internal wave travel to the sill. Middle panel: Acoustic travel times at station P2. Lower: Expansion showing alternating structure of NLIW.

alternates between a single narrow trough to the internal tide, and a wave sequence typical of internal nonhydrostatically dispersed effects.

Our analysis begins with elementary theory for nonlinear steepening of an internal wave. We assume a two-layer model with initial forcing consistent with linear internal tide generation at the sill. For an M2 tide we calculate the 'breaking distance' at which nonhydrostatic dispersion would generate high frequency waves. Rotation is not included in this calculation. The result shows the 'breaking' location roughly coincident with the first signatures showing up on remote sensing images (Fig. 6, courtesy Chris Jackson).

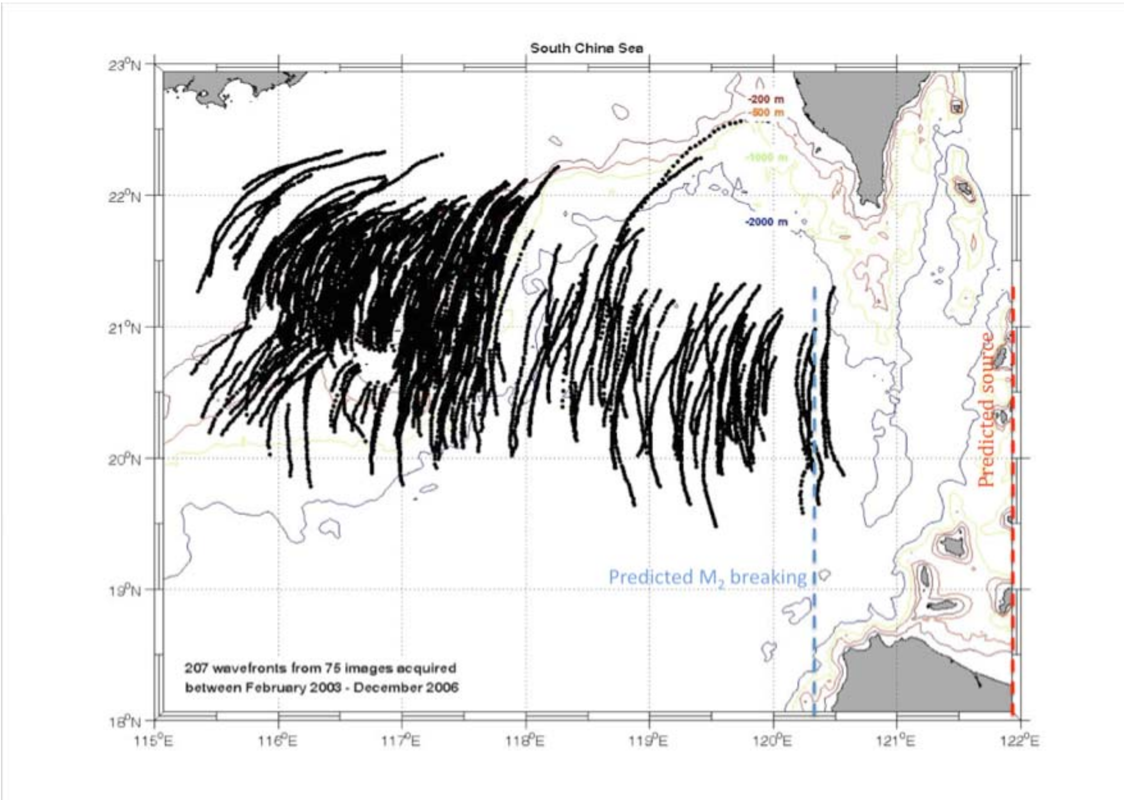

Figure 6. Location of remotely sensed surface signatures of internal waves (courtesy of Chris Jackson), assumed internal tide source (red dashed line) and predicted breaking location (blue), based on elementary nonlinear steepening theory without rotation, for M2 tide.

The same calculation breaks down for the diurnal tide due to topographic effects and rotational dispersion. Helfrich & Grimshaw have discussed other solutions of the nonlinear, non-hydrostatic rotational model, specifically generation of corner and lobate waves. In practice, given the nonlinear interaction between different frequency components we must tackle this calculation in our data with initial conditions taken from the implied interfacial slope at one location, and then checking the corresponding wave structure downstream. Figure 7 illustrates this. The dashed circles identify apparent corner waves at position 360km arising from initial conditions at 70km with required interfacial slope at position 260km. The results seem consistent with the prediction, no unambiguous observations of lobate waves were acquired.

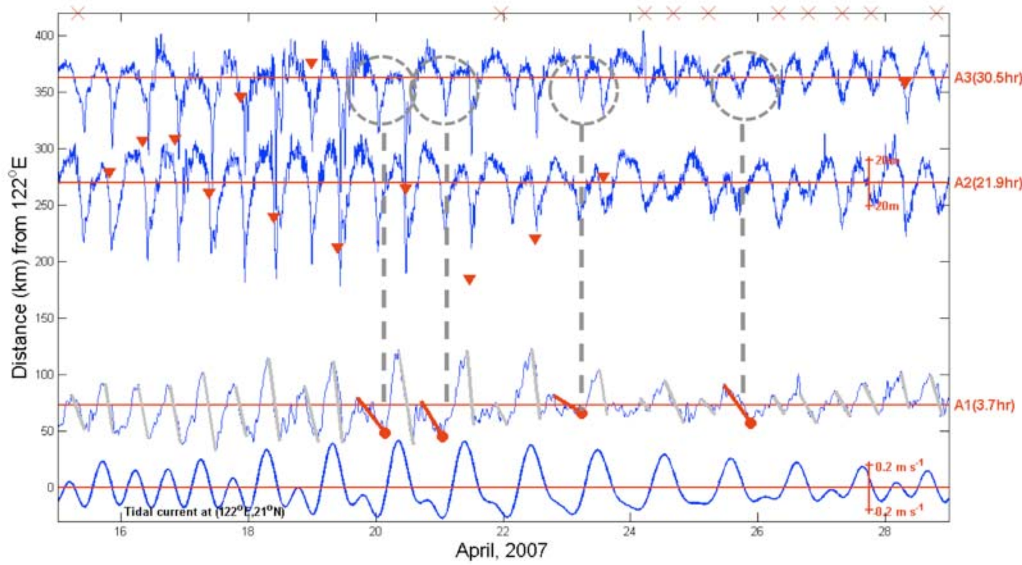

Figure 7. The lower two time series show the inferred tidal current over the Luzon sil and the measured interfacial displacement at our first observational site 70km west of the sill. The two upper curves show the time series of interfacial displacements at distances 270km and 360km respectively. The inferred interfacial slope at 70km, for which corner waves might be expected to be generated, is identified with a red bar, which is connected by a vertical dashed line to the corresponding waves at 270 and 360km. Dashed circles show waves that have the general appearance of corner waves at the corresponding 360km location.

More detailed analysis and comparison with models that include rotation illustrate its effect in suppressing steepening of the internal tide. A weakly nonlinear model of Gerkema (1996) provides a further point of comparison, including internal tide generation.

IMPACT/APPLICATIONS

Our observations have provided essential data for establishing the mechanisms of NLIW generation west of the Luzon sill. It appears that high frequency NLIW are not generated right at the sill, but evolve through nonlinearity and dispersion as the internal tide propagates west. However, rotation has an important effect in dispersing energy into inertial modes and must be included in order to develop good predictions. These observations have sufficient detail to test rotational models for NLIW and thus contribute to better predictions of appearance and behaviour.

RELATED PROJECTS

ONR project - Nonlinear Internal Waves: Test of the Inverted Echo Sounder N00014-05-1-0286.

REFERENCES

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Helfrich, Karl, 2007, Decay and return of internal solitary waves with rotation, Physics of Fluids, 19,.026601.

PUBLICATIONS

Li, Q., D. Farmer, Jae-Hun Park, Timothy F. Duda & Steve Ramp: Acoustical measurement of nonlinear internal waves using the inverted echo-sounder, *J Atmos & Oceanic Technol.*, (*submitted*).

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